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# TURBULENT MIXING AND COMBUSTION FOR HIGH-SPEED, AIR-BREATHING PROPULSION APPLICATIONS

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## Summary/Overview

This research focuses on fundamental investigations of mixing and combustion, in turbulent, subsonic, and supersonic flows and is motivated by problems in high-speed air-breathing propulsion. The work is a closely coordinated effort between experiments and numerical simulation, and exploits recent developments in diagnostics and instrumentation.

## Technical Discussion

A successful hydrocarbon-fueled scramjet engine will rely on a detailed understanding of the turbulent processes that mix fuel and air within the device, as well as the chemical kinetics and flame processes that result in conversion of the reactants to products.

Work on compressible turbulent mixing in complex geometries under this grant is focused on studying the flow control and mixing achieved in the expansion-ramp geometry (Figs. 1–2 ). In this geometry, a high-speed upper “air” stream is expanded over a ramp inclined at 30 degrees to the flow. A low-speed “fuel” stream is injected through perforations in the ramp and generates a mixing layer between the two streams. A key feature of this flow is the recirculation zone that transports hot products back toward the fuel injection location and provides a low-strain-rate flameholding region. In fully subsonic flow, the total amount of mixed fluid exiting the device was found to decrease with increasing top stream velocity for a velocity ratio of  $U_2/U_1 = 0.1$ .

Ongoing work targets flow control and mixing in the expansion-ramp geometry for supersonic top-stream flows. Figure 1 shows a composite Schlieren image from a pair of experiments with a  $M_1 = 1.5$  flow with an injection resulting in  $U_2 = 5$  m/s. The flow expands down the ramp, creating a corrugated mixing layer that interacts with the reflected waves off of the upper guidewall. The top-wall boundary layer separates upstream of the measurement rake.



Figure 1 Composite Schlieren image of the expansion-ramp flow for  $M_1=1.5$  and  $U_2=5$  m/s.

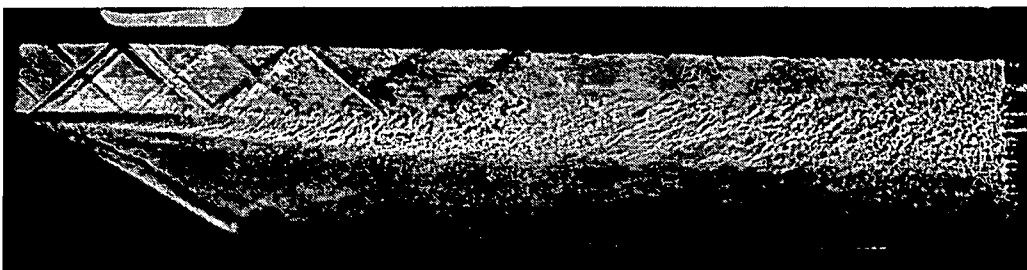


Figure 2 Composite Schlieren image of the expansion-ramp flow for  $M_1 = 1.5$  and  $U_2 = 45$  m/s.

As found for a subsonic upper stream, this flow can be controlled by varying the mass injected through the perforated ramp. Figure 2 is a composite Schlieren image for a lower-stream injection of  $U_2 = 45$  m/s and the same top-stream conditions and illustrates the considerable control that be exercised. The shear layer is almost horizontal, the upper-stream wave system remains uniform, and no boundary-layer separation occurs. A measure of the aerodynamic performance of the device is the overall pressure coefficient,  $C_p = 2(p_e - p_i)/(\rho U_1^2)$ , where  $p_e$  and  $p_i$  are the exit and inlet pressures, respectively. The pressure coefficient is plotted in Fig. 3 for the  $M_1 = 1.5$  experiments with variable injection and heat release. As expected, the slope of this profile has the opposite sign as for a subsonic inlet. As in the subsonic flow (Johnson 2005), mass injection exerts significant control authority. Addition of heat release allows the same pressure coefficient to be achieved with a mass injection almost a factor of four lower than the nonreacting flow. These experiments are being performed by J. Berghorson and A. Bonanos.

An accompanying computational effort has concentrated on verification of the complex code and simulations in complicated geometries. The Compressible LES fluid dynamics solver of the Virtual Test Facility developed under the DOE-sponsored Caltech ASC program is used for the simulations. The solver has Adaptive Mesh Refinement capabilities and implemented in a fully parallel manner with dynamic data redistribution (Pantano *et al.* 2006). The solver was verified against the theoretical predictions of the Linear Stability Analysis (LSA) theory for both free and confined spatially evolving shear layers. The growth rates from two-dimensional simulations exhibit very good agreement with the LSA predictions.

Figure 3 also shows the computed instantaneous isosurfaces of the spanwise vorticity from a three-dimensional LES using the stretched-vortex subgrid-scale model (Voelkl & Pullin 2000), with no injection through the ramp. This is the first of a series of simulations that include the complex geometry of the corresponding experiments. The computed flow shows good agreement with the experimentally observed behavior. A quantitative comparison is currently underway. The numerical simulations are part of the Ph.D. research of G. Matheou.

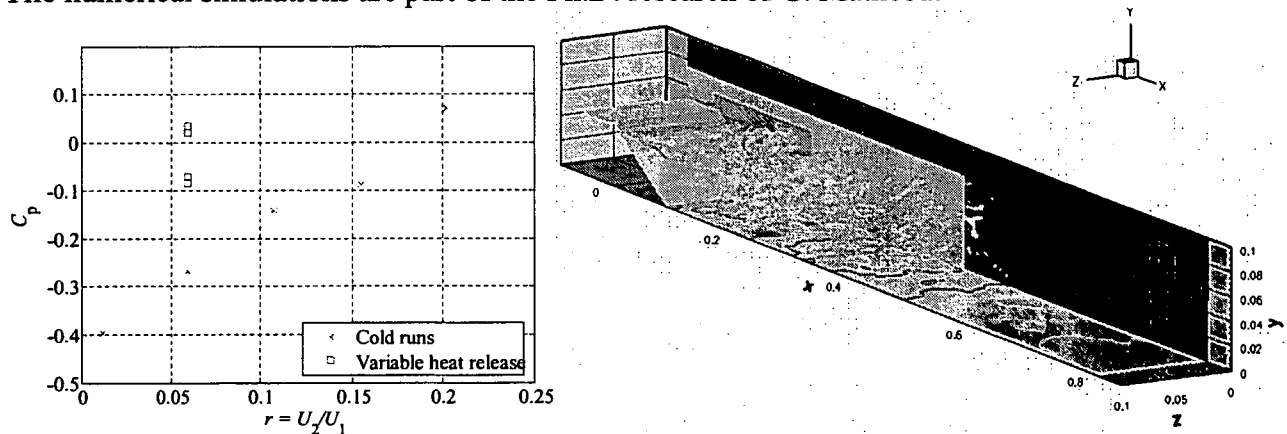


Figure 3 Left: Measured overall pressure coefficient vs. mass injection ratio and chemical heat release. Right: Computational subsonic top stream with no injection through a solid ramp (spanwise vorticity isosurfaces). Streamwise velocity contours are shown on the bottom wall and the grid density is depicted on the back wall.

A second experimental and numerical-simulation effort targets the combustion chemistry for hydrocarbon fuels of interest for scramjet propulsion applications. The dimensionality of the data sets used to validate chemical-kinetic models for hydrocarbon combustion is considerably lower than the number of constants involved leading to indeterminacies and non-uniqueness. To fully validate chemical-kinetic/thermodynamic/transport models for combustion, experimental data must be provided over a wide range of parameters. The key parameters affecting flame propagation are fuel type, mixture composition, and pressure. High accuracy measurements in methane, ethane, and diluted ethylene flames have been recorded for different compositions at

atmospheric pressure (Bergthorson and Dimotakis 2006b). The experiments provide a test-bed for systems to be integrated into variable-pressure experiments ( $p \leq 12$  atm). The approach relies on simultaneous measurements of flow velocity and CH-radical profiles in strained flames in a jet-wall stagnation flow using Particle Streak Velocimetry (PSV) and Planar Laser Induced Fluorescence (PLIF), respectively. Concurrent measurements of mixture composition and stagnation-plate temperature provide accurate boundary conditions for numerical simulations using the *Cantera* software package. These simulations rely on an axisymmetric one-dimensional hydrodynamic model, a multicomponent transport formulation, and various detailed chemistry models. This part of the work is part of the PhD research of J. Bergthorson and L. Benezech.

Systematic uncertainties in particle velocimetry are accounted for by modeling particle-inertia, thermophoretic, and finite particle-track interval effects (Bergthorson and Dimotakis, 2006a). Figure 4 shows a sample comparison of modeled-PSV profiles to PSV data in a  $\Phi = 1.0$  diluted  $C_2H_4$  flame for several state-of-the-art kinetic mechanisms: GRI-Mech 3.0, Davis-Law-Wang 1999, San-Diego 200308 and San-Diego 200503. GRI-MECH and San-Diego 200308 mechanisms significantly overpredict ethylene flame speeds, whereas the DLW99 and San-Diego 200503 predictions agree with the experiment. A new Particle Tracking Velocimetry (PTV) technique is being developed that relies on a high-power, high-repetition rate Nd:YLF laser (up to 20 kHz) and a high-resolution CCD camera (11 Mpix). The new PTV technique retains the low particle loading advantages of PSV, increasing temporal and spatial resolution, and signal amplitude at higher speeds, and will greatly expand the range of flow velocities that can be measured. Investigations of pure ethylene flames, blends of  $C_1$ - $C_2$  and hydrogen flames, and larger hydrocarbon fuels will be undertaken at variable pressure.

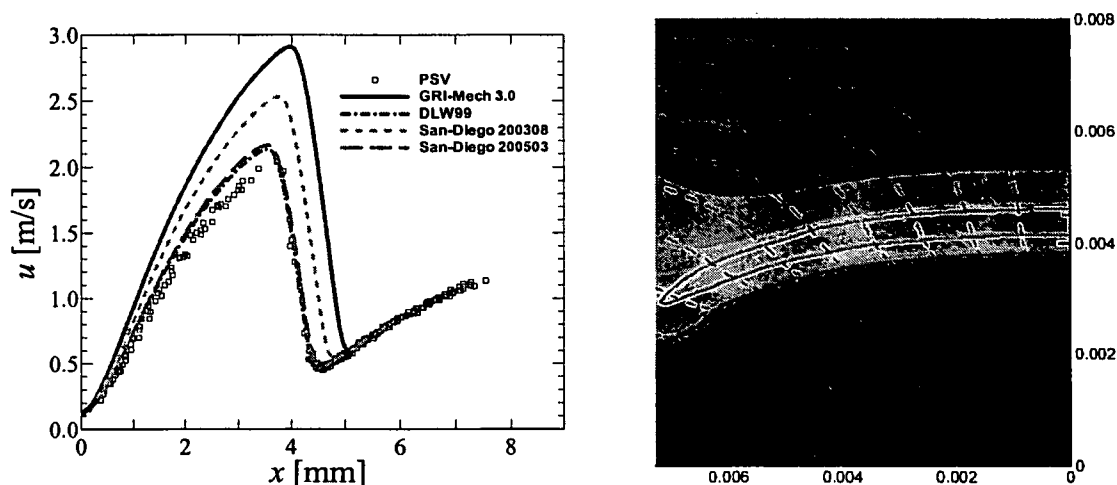


Figure 4 Left:  $\Phi = 1.0$   $C_2H_4$  flame, 17%  $O_2/(O_2+N_2)$ . Right: Two-dimensional simulation of low Mach number stagnation flame. The solid background color shows temperature field, the color solid lines represent CH mass fraction contours, and the black dashed lines represent streamlines with dash length proportional to velocity.

In a parallel numerical simulation effort, a code has been developed to perform Direct Numerical Simulations (DNS) of the experimental geometry in a 2D axisymmetric domain with detailed hydrocarbon chemistry modes that resolves all relevant length scales. The code integrates the unsteady low Mach number Navier-Stokes equations. Our new formulation satisfies both the state equation and the continuity equation while successfully removing sound waves from the simulation and allows temporal integration with time steps unrestricted by acoustic waves. The code was verified by the method of manufactured solutions and exhibits spectral convergence. A snapshot from the simulation is shown in Fig. 4 (right). This work is part of the Ph.D. research of K. Sone, performed in collaboration with D. Meiron, and cofunded by Caltech's ASC Center.

Modeling CH<sub>4</sub> combustion in air requires more than 50 species and ~ 200 reactions, or more. A state-of-the-art approach combining sensitivity analysis of laminar flame speed to each reaction rate and reaction-pathway analysis is under development to automatically identify causes of discrepancies between the predictions of multiple mechanisms. Sensitivity analysis alone already provides answers, such as in the case of the systematic overprediction of flame speeds by all mechanisms except DLW99, in an atmospheric lean methane-air flame. Sensitivity analysis first identifies reactions that affect the solution the most. Rates for these reaction rates can then be compared between mechanisms. This work is part of the PhD research of L. Benezech.

Using high frame-rate imaging with the in-house developed KFS imaging system, the NSF-funded Teravoxel high-speed/-volume data-acquisition system, and a synchronized scanning laser beam, or sheet, three- and four-dimensional imaging of the scalar field in grid turbulence was recorded for the first time, to our knowledge. Preliminary experiments were performed in the GALCIT Free Surface Water Tunnel (FSWT) at Taylor Reynolds numbers below the mixing transition of  $Re_T \sim 100$ . Extensions in optics and a new flow facility presently under development will allow such measurements to be performed over a range of Reynolds numbers spanning from below to above the mixing transition. This part of the work is performed by J. Bergthorson, D. Lang, B. Valiferdowski, and P. Dimotakis.

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